Mar Geophys Res (2013) 34:127–136
DOI 10.1007/s11001-013-9177-5

ORIGINAL RESEARCH PAPER

Continuous resistivity profiling survey in Mersin Harbour, Northeastern Mediterranean Sea

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Received: 14 January 2013 / Accepted: 30 May 2013 / Published online: 6 June 2013

Abstract No detailed information has previously been available on the geological and geophysical characteristics of the sea floor and the underlying strata of Mersin Harbour, Northeastern Mediterranean Sea (Turkey). Continuous resistivity profiling (CRP) and borehole data from Mersin Harbour were used to interpret geoelectric stratigraphy of Neogene-Quaternary sediments in the area. This represents one of few such detailed case studies that have applied these valuable CRP techniques for the purpose of marine stratigraphic imaging. It was found that the Neogene-Quaternary sedimentary succession in the area consists of three geoelectric units (GU1, GU2, and GU3 from base to top). The lowest unit, GU1, has a resistivity value of greater than 20.0 ohm-m and consists of Miocene aged limestone and marl. The middle unit, GU2, is characterized by resistivity values ranging from 3.0 to 20.0 ohm-m. Its thickness is greater than 90 m, with the upper section being composed of stiff clay sequences which are Plio-Pleistocene in age. The uppermost unit, GU3, has resistivity values varying from 1.0 to 3.0 ohm-m. This unit displays a maximum thickness of 15 m, and is composed of Holocene muds together with gravel, sand, silt and clay (sometimes incorporating shells) materials of the Plio-Pleistocene age and their various mixtures, silty/clay limestone, and conglomerate sandstone. Comparisons of the geoelectric units with the depositional sequences interpreted from the available seismic data outwith, but close to, Mersin Harbour reveal that the geoelectric unit GU3 corresponds to the depositional sequences C (mainly Holocene) and B (mainly Plio-Pleistocene). The geoelectric unit GU2 partly correlates with the depositional sequence B which appears to be Plio-Pleistocene in age. The geoelectric unit GU1, which has not been encountered in previous seismic surveys, is a new discovery within Mersin Harbour. Limited correlation between the seismic and resistivity structures in the study area is attributed to differences in the acoustic impedance and resistivity contrasts of sub-bottom layers, as well as the penetration versus resolution performance of the systems.

Keywords Marine geophysics · Resistivity profiling · Sea floor · Mersin Harbour · Turkey · Mediterranean sea

Introduction

Seismic reflection methods have been extensively used for mapping marine subsurface structures. However, in shallow waters such as harbours, water depth is always a limiting factor on bottom penetration. Moreover, the subbottom features may be masked by multiple reflections from the water bottom and the air–water interface on seismic data. In this case, other geophysical methods such as the continuous resistivity profiling (CRP) method that is used to define the electrical properties of the shallow subbottom may be applied to shallow water areas.

The CRP method recognized to be more suitable for hydrogeophysical studies in freshwater and saltwater environments is extensively used for imaging the

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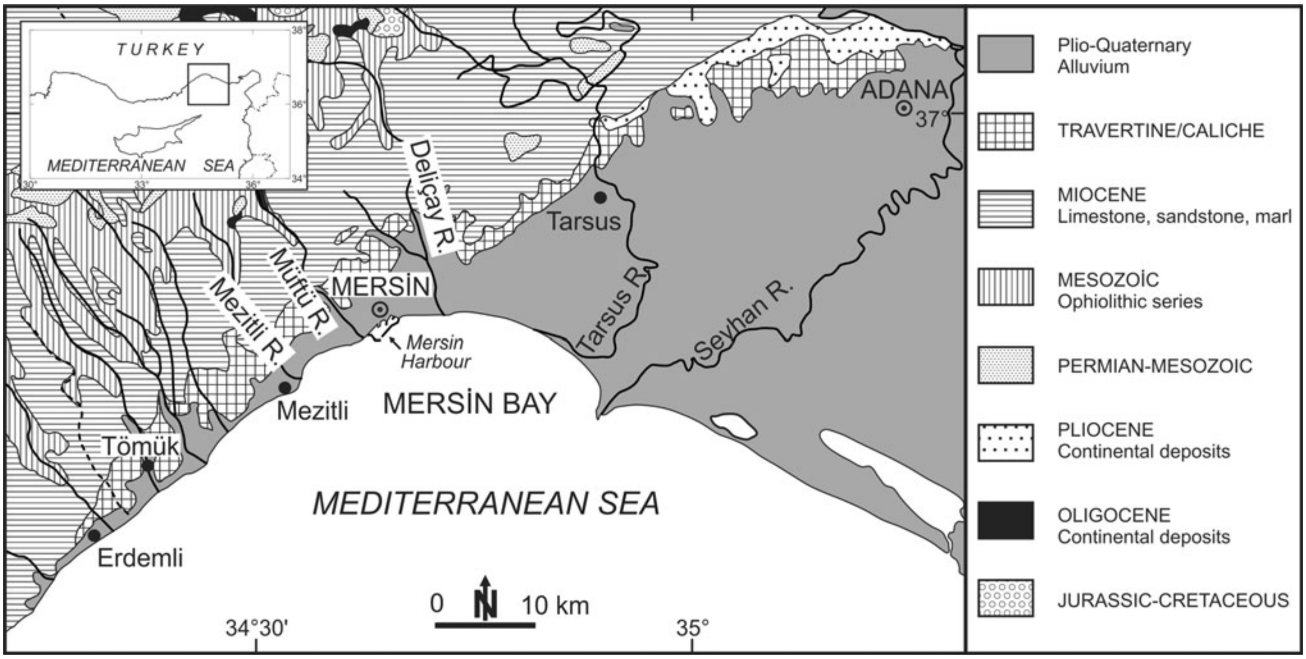

Fig. 1 Location map of the study area (inset) and geological map of the area surrounding Mersin Bay (modified from MTA 2002; Ternek 1962)

freshwater/saltwater interface (Manheim et al. 2002; Belaval et al. 2003; Bratton et al. 2005), determining submarine groundwater discharge (Manheim et al. 2002; Belaval et al. 2003; Day-Lewis et al. 2006; Swarzenski and Izbicki 2009), groundwater/surface water interaction (Heaney et al. 2007; Mitchell et al. 2008), spatial and temporal changes in pore-fluid conductivity (Mansoor and Slater 2007), buried marine archeological targets (Passaro 2010), sediment types (Snyder and Wightman 2002; Johnson and White 2007; Meunier and Swarzenski 2003) and subsurface geological structures (Kwon et al. 2005). Here, we show the advantages of the CRP method to marine stratigraphic investigations and demonstrate its utility for interpreting sedimentary packages in such a shallow water environment.

The study area, Mersin Harbour, is situated on the continental shelf of Mersin Bay in the northeastern Mediterranean Sea, Turkey (Fig. 1). The shelf of Mersin Bay is 43 km wide in the east off the Seyhan River delta and narrows down to 8.4 km near the Göksu River delta in the west. It is connected to the north by a narrow coastal plain that widens in the east-northeast towards the large fluvio-deltaic plain of the Tarsus-Seyhan-Ceyhan Rivers (Fig. 1). The narrow, alluvial Mersin plain in the southwest, composed of small coalescing alluvial fans is fed by several mainly ephemeral streams, the largest of which is the Deliçay River (Fig. 1).

The shelf morphology of Mersin Bay has been strongly influenced by fluctuations in sea level during the Quaternary (Evans 1971). Outbuilding has been caused primarily by extension of the coastal plain across the continental shelf, including the deposition of fan-delta sequences on the shelf (Ergin et al. 1992; Okyar et al. 2005).

Previous marine geophysical studies that consisted predominantly of seismic reflection surveys are related to the site investigation (IMS 1986a; Okyar et al. 1992), and seismic stratigraphic interpretation of the Quaternary deposits on the continental shelf of Mersin Bay (Bodur and Ergin 1989; Ergin et al. 1989; Okyar 1991; Aksu et al. 1992; Bodur and Ergin 1992; Ergin et al. 1992; Okyar et al. 2005). However, these previous investigations were all conducted outside Mersin Harbour; only the study by Okyar et al. (1992) was performed close to Mersin Harbour (Fig. 2). The marine resistivity measurements of the JS Geophysical Service & Advanced Technologies Co. (JS 2008) is the only marine geophysical study conducted inside Mersin Harbour. However, this technical study gives only limited information about the textural characteristics of the upper most sedimentary layer to be excavated during the dredging of the harbour, and therefore, it fails to furnish scientific knowledge for a better understanding of the geoelectrical structure of Mersin Harbour. In summary, no scientific survey has previously been conducted in the area. For this reason, comparisons of the findings from the current survey have been made with the previous seismic stratigraphic surveys carried out on the continental shelf of Mersin Bay (cf. Aksu et al. 1992; Bodur and Ergin 1992; Ergin et al. 1992; Okyar et al. 2005).

The objectives of the present study conducted inside Mersin Harbour are to identify and interpret the geoelectric

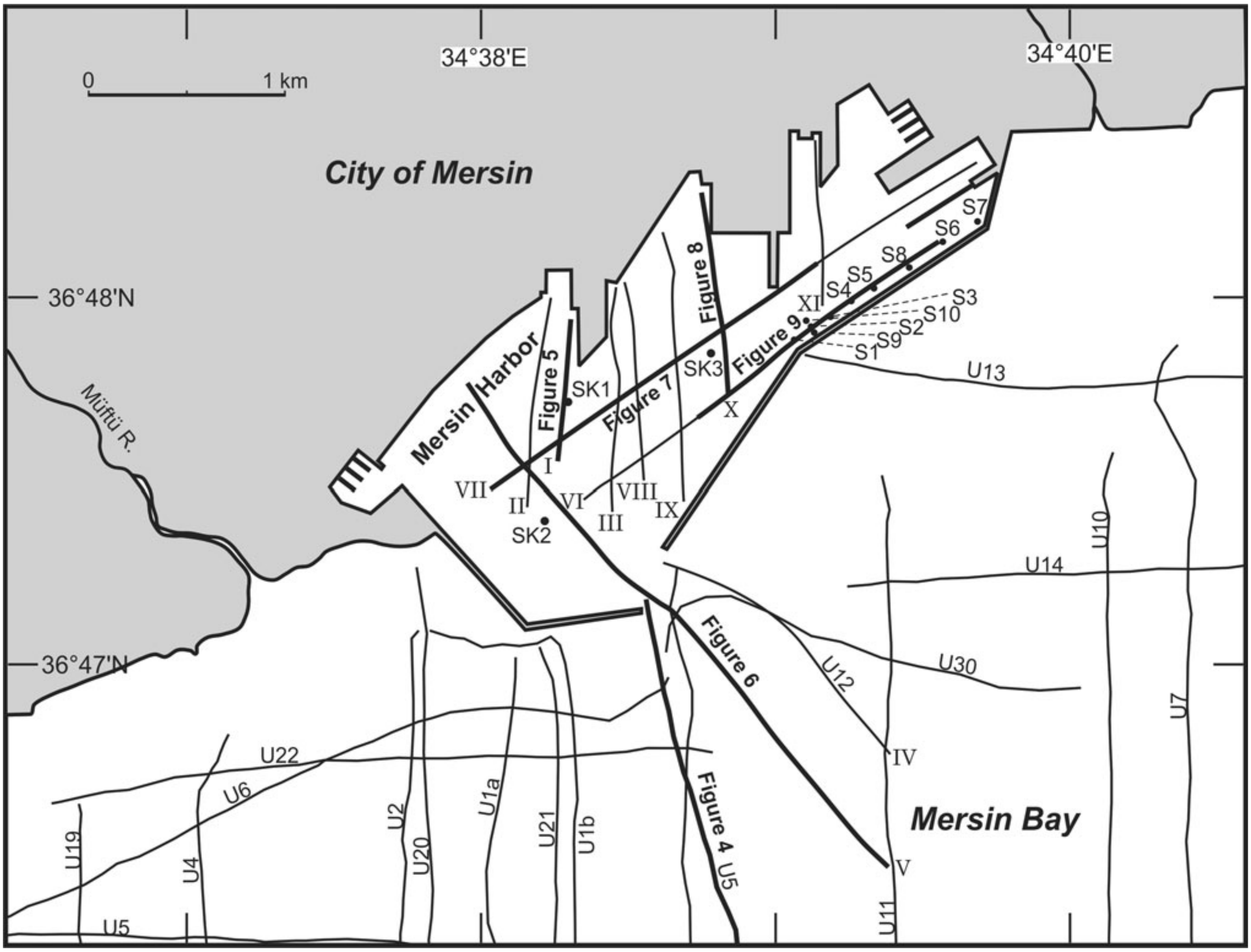

Fig. 2 Location map showing the location of the continuous resistivity profiling lines (I–XI) recorded during the current study, the location of the continuous seismic reflection profiling lines (U1a-U1b, U2, U4-U7, U10-U14, U19-U20) recorded during the 1992 survey (Okyar et al. 1992) and the location of the offshore boreholes (SK1-SK3, S1-10). Borehole logs [SK1-SK2 from the current investigation and S4 from the previous investigation of TEKAR (1988)] which are discussed in the text are shown in Fig. 3. Seismic profile shown as thick line U5 is illustrated in Fig. 4. Resistivity profiles shown as *thick lines* I, V, VII, X, and VI are illustrated in Figs. 5, 6, 7, 8, 9

stratigraphy of the Neogene-Quaternary sediments in the area, utilizing the CRP method. This will contribute to a better understanding of the composition and sedimentary evolution of the Neogene-Quaternary depositional sequences of Mersin Bay, as well as being a valuable case study of CRP application in marine stratigraphic investigations. In addition, a good knowledge of the sediment types is of fundamental importance for engineering works such as dredging and channel opening.

Geologic and hydrographic setting

The geology of the coast surrounding Mersin Harbour is dominated by Plio-Quaternary deposits overlying late Tertiary [mainly Neogene (Miocene)] limestones, marls, sandstones and conglomerates (DSI 1978; and unpublished data) (Fig. 1). Plio-Quaternary deposits are composed mainly of clay, silt, sand and gravel of diverse origins. Gravel-sized materials contain fragments of limestone, chert, sandstone, and basic/ultramafic rocks.

The Plio-Quaternary deposits on the coastal plain reach a maximum thickness of 1,250 m in the vicinity of the Seyhan River (Schmidt 1961). Extending southward, within the Mediterranean Sea, the Plio-Quaternary sequences range in thickness from <250 m on the shelf/upper slope zone to 1–2 km (Stanley 1977; Woodside 1977; Özhan 1988).

Surface sediment patterns show that siliciclastic mud is the dominant type on the Mersin Bay shelf, and sand and gravel are frequently found beneath the nearshore waters at depths of <10 m (Shaw and Bush 1978; Ediger et al. 1997). The Seyhan, Tarsus, Deliçay, Müftü and Mezitli rivers provide the majority of sediments to Mersin Bay. Of these, the Seyhan and Tarsus flow all year round, while the others constitute ephemeral flows for 3–4 months of the year. However, after its construction in 1954, the harbour breakers significantly reduced the sediment supply to Mersin Harbour (classified as Prodeltaic Zone-I, based on the surficial sediment classification of Ediger et al. 1997) from the main rivers, the Seyhan, Tarsus and Deliçay.

Mersin Bay is characterized by the westward flow of surface currents (Lacombe and Tchernia 1972; Ünlüata et al. 1978). However, several cyclonic and anticyclonic circulation systems, which may extend to the shelf edge, are produced by local winds and coastal morphology (Collins and Banner 1979). The near-surface current velocities vary between 10 and 30 cm/s, although much greater fluctuations occur (3–57 cm/s) under changing hydrographic conditions (IMS 1986b).

Materials and methods

Marine electrical resistivity and borehole data used in this study were collected in April 2008 (Fig. 2). The CRP survey was conducted using a Marine SuperSting R8/IP (Advanced Geosciences Inc.) system and a specially designed streamer cable of 400 m in length with 11 electrodes (two current electrodes and nine potential electrodes) spaced at 20 and 40 m configured in a dipole–dipole array. This arrangement yielded the investigation depths of 40 and 90 m. The streamer was towed across the sea surface at speeds of about 2–3 knots to acquire more data points. The R8/IP is an eight channel instrument and injects a current of up to 2 amps with a maximum power output of 200 watts. In resistivity mode it can store more than 79,000 measurements. Measurement-stacking cannot be made in CRP systems due to towing electrodes (e.g. Belaval et al. 2003). A Lowrance 332C GPS/Sonar unit connected to the SuperSting marked position and water depth during the surveys. Real time sea-surface water temperature measurements were continuously recorded along the survey lines using a multi-meter. Borehole data were obtained by the D500 Craelius drilling machine.

Additional borehole data, drilled by the TEKAR (1988) program, are also presented in this study.

Resistivity data were processed to prepare two-dimensional models using the EarthImager 2D software developed by Advanced Geosciences Inc. EarthImager 2D discretized the subsurface model into a finite element grid. The finite element model of electrical resistivities is automatically modified through an iterative process, so that the model response converges towards the measured data. For the nonlinear inversion of the simulated data, EarthImager 2D's smooth model inversion algorithm and an average apparent resistivity homogenous starting model were used. The inversion method adjusts the 2D resistivity model trying to iteratively reduce the difference between the calculated and observed resistivity values. The root mean squared (RMS) error provides a measurement of this difference. In all the inversion processes, the number of iterations varied between 8 and 10 with RMS error ranging from 15 to 18 %. These RMS errors in the inversion may be due to noises and gaps in the data.

Results and discussion

Offshore lithofacies

In Mersin Harbour, four boreholes drilled at water depths of 10, 9, 8.25 and 6 m provide lithological information on the sedimentary sequences (Fig. 3). On the basis of the previous studies by Ergin (1996) and Okyar et al. (2005), it can be suggested that the sedimentary successions observed in the borehole logs are comprised of Holocene and Plio-Pleistocene deposits. Of these mud layers in the upper parts of all the boreholes SK1, SK2, SK3, and S4 (Fig. 3) are considered to be Holocene in age, and the sedimentary layers below the mud unit are inferred to be Plio-Pleistocene in age.

The boundary between the Holocene mud and the Plio-Pleistocene deposits was well-defined on the high resolution seismic reflection profiles (Fig. 4) from the close vicinity of Mersin Harbour. The prominent reflector, Reflector R (Ergin et al. 1992; Okyar et al. 2005), separating Holocene (sequence C) from Plio-Pleistocene (sequence B) sediments is interpreted as the pre-Holocene surface.

The lithologies encountered in the boreholes are given below.

Borehole SK1: The top of this borehole is represented by a 1 m thick deposit of dark grey mud underlain by a gravelly shelly sand layer extending down to a depth of 11.7 m (Fig. 3). Below this layer, a light brown silty sand layer to a depth of 13 m is observed. This layer is underlain by a light brown slightly gravelly silty clay layer down to a depth of 14 m. A silt layer is present below this layer to a depth of 15 m.

Borehole SK2: The upper lithostratigraphic unit in this borehole again consists of dark grey mud about 1 m thick, as in Borehole SK1 (Fig. 3). From the base of this layer, a gravelly shelly sand layer to a depth of 10 m is present. This layer is underlain by a brown and beige veined slightly gravelly silty clay layer to a depth of 13 m. Next a layer of grey-yellowish sand is encountered to 15 m depth. This layer is underlain by a silty clay layer down to a depth of 15.7 m. Below this is a layer of light brown silty-clayey limestone about 1.3 m thick.

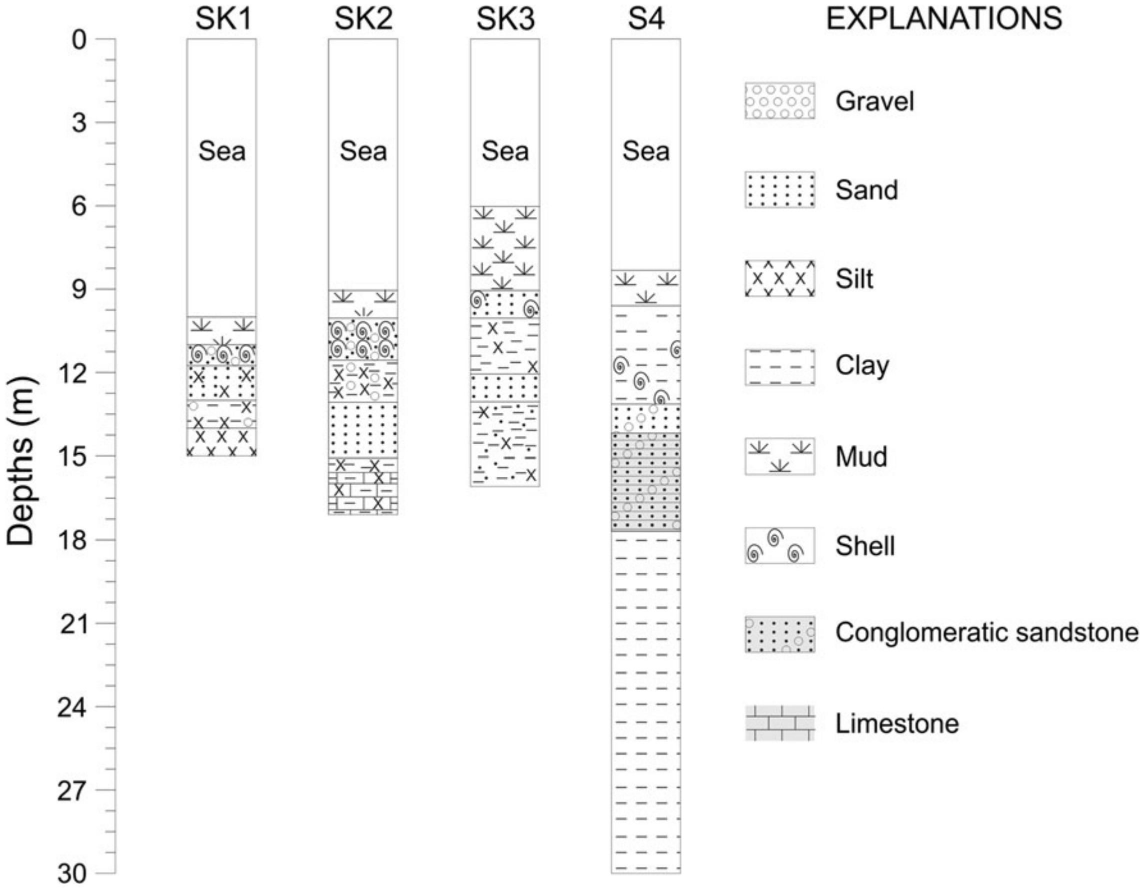

Fig. 3 Lithological logs of the offshore boreholes (see Fig. 2 for location)

Borehole SK3: As in the two previous boreholes (SK1 and SK2), at the top of this borehole, a layer of dark grey mud about 3 m thick overlies a shelly sand layer that extends to a depth of 10 m (Fig. 3). From the base of the shelly sand layer a layer of light yellowish silty clay is present to a depth of 12 m. From this depth to a depth of 13 m a layer of light grey-brown sand is observed. This layer is underlain by a layer of silty sandy clay.

Borehole S4: The top of this borehole displays a layer of greenish gray to grayish olive mud about 1.5 m thick (Fig. 3). Between the depths of 9.6 and 13.2 m, stiff, brown shelly clay layers appear. These clay layers are underlain by gravelly sand layers up to 1 m thick. From the base of these layers down to 17.7 m depth, conglomerate sandstone layers appear. Deeper still, stiff clay layers, reddish to brown in colour appear.

According to Okyar et al. (2005), brown-colored stiff shelly clay sections between 9.6 and 13.2 m depths imply the effects of subaerial weathering due to sea level lowering during the late Quaternary, whereas the presence of shells suggests marine depositional conditions.

Sub-bottom resistivity structure

Interpretation of the inverted CRP sections (Figs. 5, 6, 7, 8, 9) reveals the presence of three sub-bottom geoelectric units (GU1, GU2, and GU3 from base to top). Additionally, in the sections, the relatively low resistivities (<1 ohm-m) correspond to sea water, which is detected to a depth of approximately 12 m from surface to sea floor.

Geoelectric unit GU1: The geoelectric unit GU1 which is intermittent along the base of the resistivity profiles I (Fig. 5), VII (Fig. 7), and X (Fig. 8) is the lowest layer underlying the GU2 and GU3. The resistivity value of GU1 is greater than 20 ohm-m. Boreholes drilled in the coastal zone to the northwest of the surveyed area (i.e. off the Susanoğlu-Tırtar coasts and Karapınar-Gilindirez river mouths and which are not shown in the figures) suggest the presence of Miocene aged limestone and marl which crop out on the coast. Therefore, the geoelectric unit GU1 correlates closely with these lithologies which are Miocene age.

Geoelectric unit GU2: The geoelectric unit GU2 rests directly on the GU1 and displays a resistivity varying from 3.0 to 20.0 ohm-m (Figs. 5, 6, 7, 8, 9). The thickness of

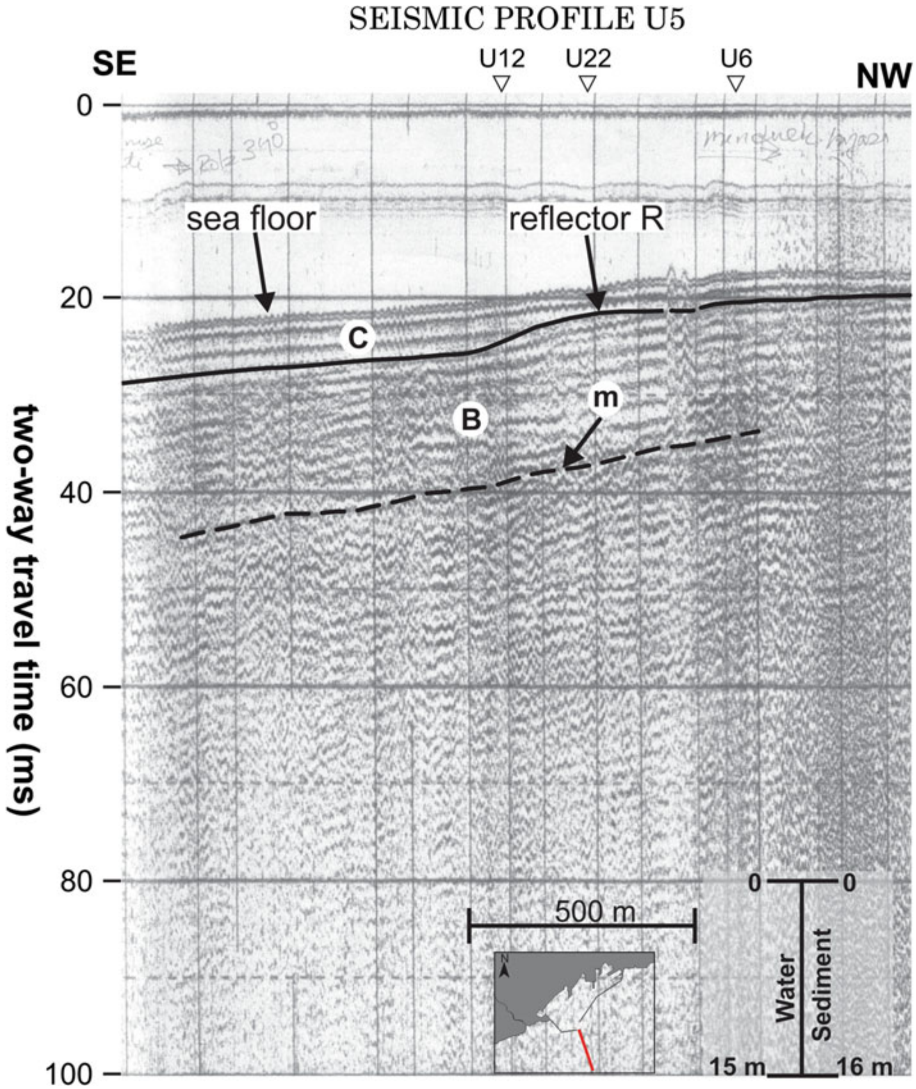

Fig. 4 High-resolution seismic reflection profile U5 obtained from the surrounding marine regions of the Mersin Harbor showing the two distinct depositional sequences (C and B) separated by a reflector R which is interpreted as the pre-Holocene surface (e.g. Ergin et al. 1989; Okyar 1991; Okyar et al. 1992, 2005). The upper sedimentary sequence C was though to represent the Holocene, and the lower sedimentary sequence B was interpreted as having formed largely during the Plio-Pleistocene. The 'm' indicates a multiple. *Inverse triangles* indicate location of intersection with other survey *lines*. For location see Fig. 2

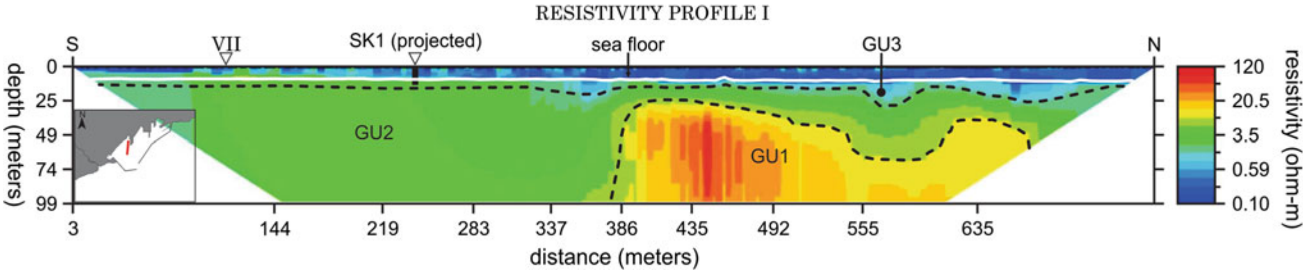

Fig. 5 Resistivity profile I with interpretation. GU1, GU2, and GU3 denote the geoelectric units discussed in the text. Borehole SK1 is projected on the profile. *Inverse triangle* indicates location of intersection with other survey line. For location of all profiles, see Fig. 2

GU2 is greater than 90 m. Borehole S4 (Fig. 3) projecting onto the resistivity profile VI (Fig. 9) implies that the upper parts of the GU2 must have consisted of stiff clay sequences which are considered to have been deposited during the Plio-Pleistocene.

Geoelectric unit GU3: The geoelectric unit GU3 is the upper sedimentary sequence the top of which forms the present sea floor (Figs. 5, 6, 7, 8, 9). This unit is characterized by electric resistivity values ranging from 1.0 to 3.0 ohm-m. The GU3 reaches a maximum thickness of 15 m in the central area of the harbour. However, it is absent in some places where the GU2 outcrops on the sea floor (e.g. southeastern section of the resistivity profile X, Fig. 8).

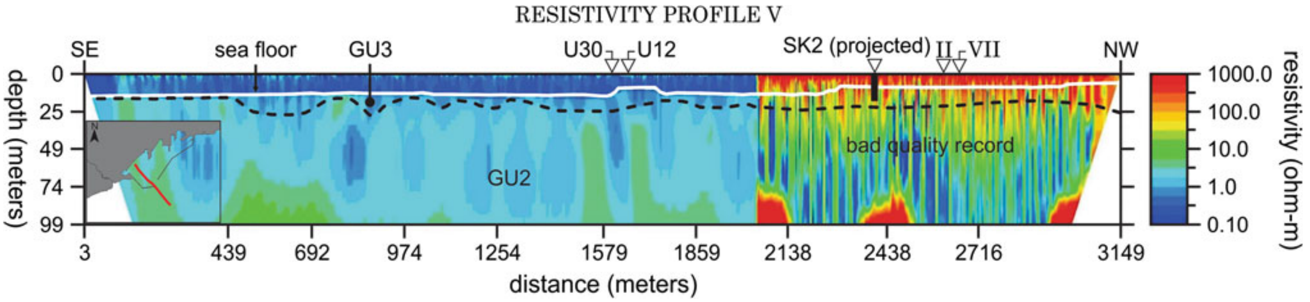

Fig. 6 Resistivity profile V with interpretation. GU2 and GU3 denote the geoelectric units discussed in the text. Borehole SK2 is projected on the profile. *Inverse triangles* indicate location of intersection with other survey lines

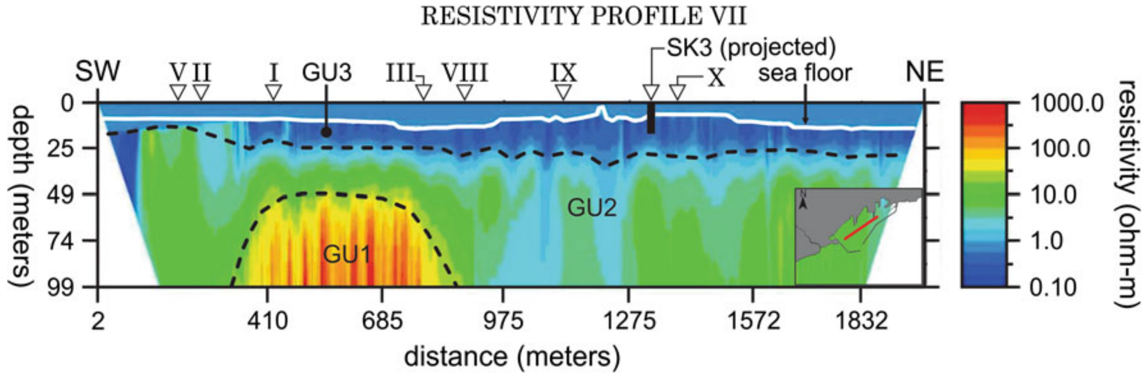

Fig. 7 Resistivity profile VII with interpretation. GU1, GU2, and GU3 denote the geoelectric units discussed in the text. Borehole SK3 is projected on the profile. *Inverse triangles* indicate location of intersection with other survey *lines*

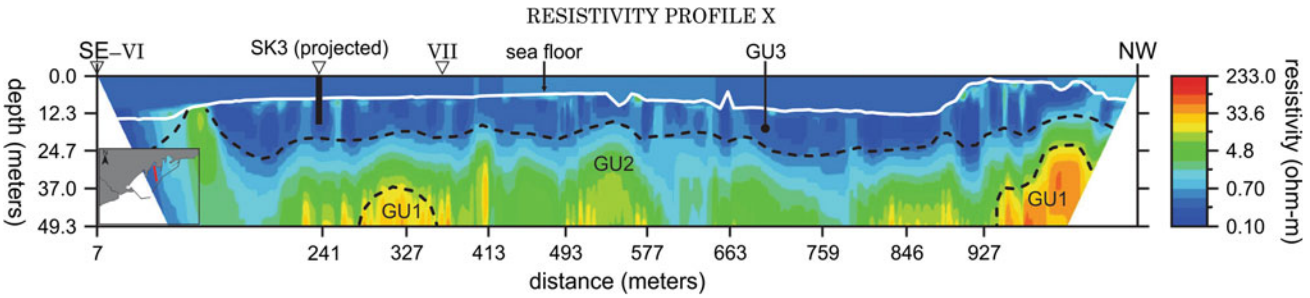

Fig. 8 Resistivity profile X with interpretation. GU1, GU2, and GU3 denote the geoelectric units discussed in the text. Borehole SK3 is projected on the profile. *Inverse triangle* indicates location of intersection with other survey *line*

Projections of the borehole logs SK1, SK2, SK3, and S4 (Fig. 3) with the resistivity profiles I (Fig. 5), V (Fig. 6), VII (Fig. 7), X (Fig. 8), and VI (Fig. 9) suggest that this unit consists of both Holocenic and the Plio-Pleistocenic sediments. As stated earlier, the Holocene deposits are composed of mud; and the Plio-Pleistocene deposits are comprised of gravel, sand, silt and clay (sometimes incorporating shells) materials and their various mixtures, silty clayey limestone, and conglomerate sandstone.

From this we can conclude that the geoelectric unit GU3 interpreted in this present study corresponds to the sequences C (Holocene) and B (Plio-Pleistocene) inferred in the previous seismic surveys of Ergin et al. (1989), Okyar (1991) and, Okyar et al. (1992, 2005).

Conclusions

CRP supported by borehole data in Mersin Harbour, Turkey, has revealed the existence of three geoelectric units (GU1, GU2, and GU3) in the Neogene-Quaternary succession of Mersin Harbour. The lowest unit, GU1, has a resistivity value of greater than 20 ohm-m. Based on boreholes which were drilled in the coastal zone to the

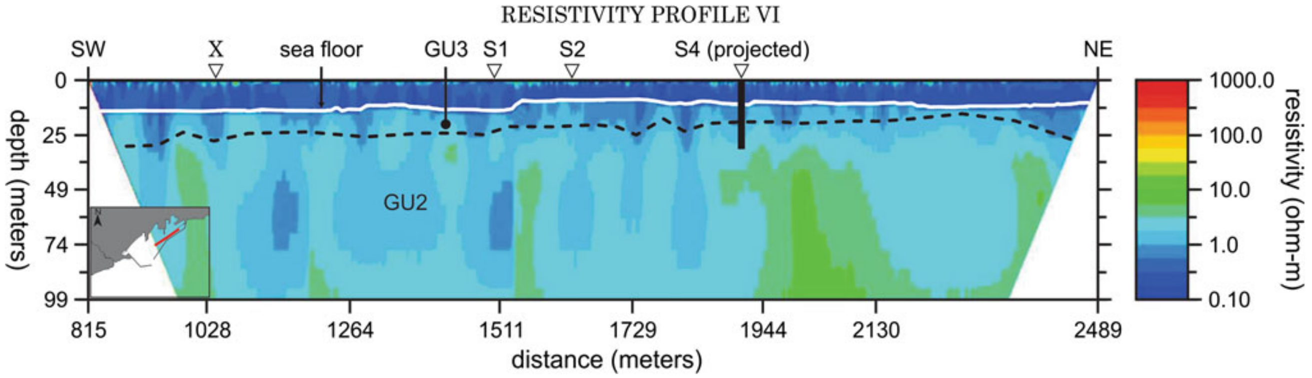

Fig. 9 Resistivity profile VI with interpretation. GU2 and GU3 denote the geoelectric units discussed in the text. Borehole S4 is projected on the profile. *Inverse triangle* indicates location of intersection with other survey *line* and boreholes

northwest of the surveyed area, the geoelectric unit GU1 can correlate well with Miocene aged limestone and marl sequences. On the other hand, taking the resistivity values of the geoelectric units of GU1, GU2, and GU3 into consideration, it is seen that there is a consistent trend of increasing resistivites of the units with depth. This may imply decreased porosity of the geoelectric units with depth, mainly through compaction (e.g. Belaval et al. 2003). The middle unit, GU2, is characterized by resistivity values ranging from 3.0 to 20.0 ohm-m, with a thickness of over 90 m. It is composed of the stiff clay sequences which are considered to have accumulated during the Plio-Pleistocene era. Shelf seismic studies of Ergin et al. (1992), and Okyar et al. (2005), showed that Plio-Pleistocene substratum have been subjected to the climatic fluctuations and oscillating sea-level changes.

The upper unit, GU3, displays resistivity values ranging from 1.0 to 3.0 ohm-m and has a maximum thickness of 15 m. This unit is made up of Holocene-aged mud, and Plio-Pleistocene-aged gravel, sand, silt, and clay sediments, sometimes containing shells, and their various mixtures, silty clayey limestone, and conglomerate sandstone. No unconformity separating the Holocene deposits from the Plio-Pleistocene sediments was observed on the CRP data. However, the shelf seismic study of Ergin et al. (1992) gives a Holocene sedimentation rate ranging from 1 to 3.5 m/ka for the inner and mid-shelf areas of the eastern Mersin Bay. According to Okyar et al. (2005), during the Holocene period in eastern Mersin Bay, sediment transportation from the main rivers, Seyhan, Ceyhan, Tarsus and Deliçay occurred in a southwesterly direction, parallel to the main current of the northeastern Mediterranean.

Considering previous high-resolution seismic works carried out close to Mersin Harbour (Bodur and Ergin 1992; Ergin et al. 1992; Okyar et al. 2005), the sequences C (mainly Holocene) and B (mainly Plio-Pleistocene) interpreted from the seismic data have been correlated with the upper geoelectric unit, GU3, observed on the resistivity profiles. Therefore, the reflector R, the pre-Holocene surface, separating sequences C and B could not be resolved on the resistivity profiles. This can be related to the different seismic (high acoustic impedance) and electrical (poor resistivity contrast) properties of the sub-bottom layers. Since both the depositional sequence B and the upper sections of the geoelectric unit GU2 are Plio-Pleistocene in age, they appear to be correlated with each other. Additionally, the lowest geoelectric unit, GU1, which is observed on the resistivity profiles, has been identified for the first time in Mersin Harbour. This unit has not been discriminated on the seismic reflection profiles close to the surveyed area, which is related to the limited penetration depth of the seismic system used.

On the seismic data, some acoustically opaque zones within the Holocene sequence (C) were interpreted as an indication of entrapped gas bubbles produced by the degradation of organic matter, and/or upward movement of land-derived ground water into the nearshore sediments (Ergin et al. 1992; Okyar et al. 2005). However, in the study area no marine groundwater discharges were delineated.

Additionally, any faulting in the bottom and sub bottom layers has not been detected in the CRP data. These results are consistent with the findings of the previous seismic survey on the eastern shelf area of Mersin Bay (Ergin et al. 1992).

Acknowledgments We would like to thank Editor-in-Chief Dr. Amy Draut, reviewer Dr. Tim Eaton and one anonymous reviewer for their constructive criticism, which have contributed to important improvements in this paper.

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